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The CMS Collaboration*

Abstract

A search for baryon number violation (BNV) in top-quark decays is performed using pp collisions produced by the LHC at $\sqrt{s} = 8$ TeV. The top-quark decay considered in this search results in one light lepton (muon or electron), two jets, but no neutrino in the final state. Data used for the analysis were collected by the CMS detector and correspond to an integrated luminosity of 19.5 fb^{-1}. The event selection is optimized for top quarks produced in pairs, with one having the BNV decay and the other the standard model hadronic decay to three jets. No significant excess of events over the expected yield from standard model processes is observed. The upper limits at 95% confidence level on the branching fraction of the BNV top-quark decay are calculated to be 0.0016 and 0.0017 for the muon and the electron channels, respectively. These limits are the first that have been obtained on a BNV process involving the top quark.

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*See Appendix A for the list of collaboration members

1 Introduction

In the standard model (SM) of particle physics [1–3], baryon number is a conserved quantity as a consequence of an accidental symmetry of the Lagrangian. In fact, it has been proven that extremely small violations can arise from non-perturbative effects [4]. Baryon number violation (BNV) is also predicted in several scenarios of physics beyond the SM such as supersymmetry [5, 6], grand unification [7], and models with black-holes [8]. Furthermore, BNV is a necessary condition for the observed asymmetry between baryons and antibaryons in the Universe, assuming an evolution from a symmetric initial state [9].

Despite these compelling reasons, no direct evidence of BNV processes has been found to date. Experiments have set stringent limits on BNV in nucleon [10], τ-lepton [11–13], heavy-meson [14, 15], and Z boson [16] decays. The possibility that BNV could occur in the decay of the top quark (t) was first considered in Ref. [17], in which a very stringent bound of about 10^{-27} was derived on the branching fraction of the decay $\mathrm{t} \to \overline{\mathrm{b}}\overline{\mathrm{c}}\ell^+$ using the experimental bound on the proton lifetime [10]. However, more recently it has been noted [18] that cancellations between different four-fermion interactions could allow much higher rates of occurrence for the BNV decays $\mathrm{t} \to \overline{\mathrm{b}}\overline{\mathrm{c}}\mu^+$ ($\bar{\mathrm{t}} \to \mathrm{bc}\mu^-$) and $\mathrm{t} \to \overline{\mathrm{b}}\overline{\mathrm{u}}\mathrm{e}^+$ ($\bar{\mathrm{t}} \to \mathrm{bue}^-$) with a muon and an electron, respectively, in the final state. Other BNV decays of the top quark, involving different flavors for the lepton and jets, are also discussed in Ref. [18], where in all cases they are described as four-fermion effective interactions, in which both baryon number and lepton number are violated.

In this Letter we search for evidence of such BNV top-quark decays using $19.52 \pm 0.49\,\mathrm{fb}^{-1}$ of pp collision data at $\sqrt{s} = 8\,\mathrm{TeV}$, collected in 2012 with the Compact Muon Solenoid (CMS) detector [19] at the Large Hadron Collider (LHC). These decays are referred to as "BNV decays" in the following, as opposed to the SM decay of the top quark into a W boson and a bottom quark. Assuming that the BNV decay branching fraction ($\mathcal{B}$) is $\ll 1$, the most suitable process for its observation is expected to be pair production of top quarks ($\mathrm{t\bar{t}}$), where one top quark undergoes a SM decay into three jets and the other the BNV decay. This process would have the highest cross section among those involving at least one BNV decay and could be effectively separated from background. Two event selections, one for the muon and one for the electron channel, are defined and optimized for such a process. In both cases the final state consists of an isolated lepton, five jets, and no neutrino.

2 The CMS detector

The central feature of the CMS apparatus is a 3.8 T superconducting solenoid of 6 m internal diameter. Inside the coil are the silicon pixel and strip tracker, the lead-tungstate crystal electromagnetic calorimeter (ECAL), and the brass and scintillator hadron calorimeter. Muons are detected by gas-ionization detectors embedded in the steel flux-return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. A two-stage trigger system selects pp collision events of interest for use in physics analyses. CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the LHC plane), and the z axis pointing along the counterclockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the x-y plane. Muons (electrons) are reconstructed and identified in the pseudorapidity ($\eta = -\ln[\tan(\theta/2)]$) range $|\eta| < 2.4(2.5)$. The inner tracker measures charged particle trajectories within the pseudorapidity range $|\eta| < 2.5$, and provides an impact parameter resolution of $\sim 15\,\mu\mathrm{m}$. A detailed description of the CMS detector can be found elsewhere [19].

3 Trigger and datasets

The data used for this analysis were collected using isolated-lepton (muon or electron) plus multijet triggers. In the muon (electron) trigger an isolated muon (electron) candidate is required to have a transverse momentum p_T greater than 20 (25) GeV/c, $|\eta| < 2.1$ (2.5), and be accompanied by at least three jets in the central region, with $p_T > 45, 35, 25$ $(50, 40, 30)$ GeV/c. The trigger efficiency for signal events passing the offline selection, described in Section 4, is 83% (80%) for the muon (electron) analysis.

A number of simulated event samples with the most important backgrounds are used to compare observations with SM expectations. The $t\bar{t}$ +jets, W+jets, and Z+jets events are generated with the MADGRAPH v5.1.3.30 event generator [20]. The top-quark mass is set to 172.5 GeV/c^2 and the branching fraction of top-quark decays to a W boson and a b quark is assumed to be one. MADGRAPH is interfaced with PYTHIA v6.426 [21] to simulate parton fragmentation and hadronization. For each production process, data samples corresponding to 0, 1, 2, and 3 extra partons are merged using the "MLM" matching prescription [22] in order to yield a realistic spectrum of accompanying jets. Diboson and QCD multijet events are generated with PYTHIA, whereas single-top-quark samples are generated with POWHEG [23, 24]. Samples of $t\bar{t}$W and $t\bar{t}$Z events with up to one extra parton are generated with MADGRAPH.

A number of signal samples are generated with MADGRAPH v5.1.4.3 [25] interfaced with PYTHIA v8.165 [26]. Two of these samples correspond to events with $t\bar{t}$-pair production in which one or both top quarks have a BNV decay. Three other simulated signal samples correspond to the tW, t-channel, and s-channel processes giving rise to single top-quark production. In each of these cases the top quark has a BNV decay, and samples corresponding to zero and one extra parton are merged. All the fermion-flavor-dependent parameters, which appear in the effective BNV Lagrangian defined in [18], were set to unity. Different choices for these values can in principle lead to variations in the kinematical distributions of the top-quark decay products, but the resulting impact on the final results of the search is negligible.

For all simulated samples, the hard interaction collision is overlaid with a number of simulated minimum-bias collisions. The resulting events are weighted to reproduce the distribution of the number of inelastic collisions per bunch crossing (pileup) measured in data.

A detailed simulation of particle propagation through the CMS apparatus and detector response is performed with the GEANT4 v9.2 [27, 28] toolkit.

4 Event reconstruction and selection

The signal search is performed by counting events passing a "tight" selection. As explained in Section 5, the sensitivity of the search is substantially improved by also using a "basic" selection that includes the tight one. These two event selections are described below.

4.1 Basic selection

Events are reconstructed using a particle-flow (PF) algorithm [29], which consists in reconstructing and identifying each single particle with an optimized combination of all subdetector information. Reconstructed particles are categorized into muons, electrons, photons, charged hadrons and neutral hadrons. At least one primary vertex is required to be reconstructed in a cylindrical region defined by the longitudinal distance $|z| < 24\,\mathrm{cm}$ and radial distance $r < 2\,\mathrm{cm}$ relative to the center of the CMS detector. The average number of reconstructed primary vertices per event is approximately 15 for the entire 2012 data taking period. The reconstructed primary vertex with the largest $\sum p_{\mathrm{T}}^2$ of all associated tracks is assumed to be produced by the hard-scattering process. All reconstructed muons, electrons and charged hadrons used in this analysis are required to be associated with this primary vertex.

Muons are identified by performing a combined fit to position measurements from both the inner tracker and the muon detectors [30]. They are required to have $p_{\mathrm{T}} > 25\,\mathrm{GeV}/c$ and $|\eta| < 2.1$. Their associated tracks are required to have measurements in at least six of the inner tracker layers, including at least one pixel detector layer, a combined fit χ^2 per degree of freedom smaller than 10, and to be reconstructed using at least two muon detector layers. In addition, the transverse (longitudinal) impact parameter of the muon track relative to the reconstructed primary vertex is required to be smaller than 0.2 cm (0.5 cm).

Electrons are identified [31] as tracks reconstructed in the inner tracker with measured momenta compatible with their associated energy depositions in the ECAL. Electrons are required to have $p_{\mathrm{T}} > 30\,\mathrm{GeV}/c$ and $|\eta| < 2.5$, with the exclusion of the transition region between barrel and endcaps defined by $1.444 < |\eta| < 1.566$. The transverse (longitudinal) impact parameter of the electron track relative to the reconstructed primary vertex is required to be smaller than 0.02 cm (0.1 cm). These requirements are tighter than in the case of muons in order to reject electrons originating from photon conversions, and misidentified hadrons coming from pileup collisions. Additional photon conversion rejection requirements [31] are also applied.

Muon and electron candidates are required to be isolated. Isolation is defined via the variable

$$I_{\mathrm{rel}}^{\ell} = \frac{E_{\mathrm{ch}} + E_{\mathrm{nh}} + E_{\gamma}}{p_{\mathrm{T}}^{\ell}}, \tag{1}$$

where p_{T}^{ℓ} is the lepton transverse momentum, E_{ch}^{ℓ} is the transverse energy deposited by charged hadrons in a cone with aperture $\Delta R = 0.4$ (0.3) in (η, ϕ) around the muon (electron) track, and E_{nh}^{ℓ} (E_{γ}^{ℓ}) is the transverse energy of neutral hadrons (photons) within this cone. The transverse energies in Eq. (1) are defined as the scalar sum of the transverse momenta of all contributing particles. Muon (electron) candidates are required to have $I_{\mathrm{rel}}^{\ell} < 0.12$ (0.10).

Events with one lepton candidate satisfying the above criteria are selected for further consideration. Events with one or more additional reconstructed muons (electrons) with $p_{\mathrm{T}} > 10$ (15) GeV/c, $|\eta| < 2.5$, $I_{\mathrm{rel}}^{\ell} < 0.2$ are rejected.

All the particles identified by the PF algorithm that are associated with the primary vertex are clustered into jets using the anti-k_{T} algorithm [32] with a distance parameter of 0.5. Corrections to the jet energy scale are applied to account for the dependence of the detector response to jets as a function of η and p_{T} and the effects of pileup [33]. The energy of reconstructed jets in simulated events is also smeared to account for the 5–10% discrepancy in energy resolution that is observed between data and simulation [33]. At least five jets are required with $p_{\mathrm{T}} > 70, 55, 40, 30, 30\,\mathrm{GeV}/c$ and $|\eta| < 2.4$. The offline jet p_{T} thresholds are chosen such that all selected jets are in the trigger efficiency plateau. In addition, at least one of these jets must be b-tagged by the "combined secondary-vertex" (CSV) algorithm tuned for high efficiency [34]. This algorithm combines information about the impact parameter of tracks and reconstructed secondary vertices within the jet. Its typical efficiency for tagging b-quark jets is about 90%, whereas the mistagging efficiency, for jets produced by the hadronization of light quarks (u, d, s) or gluons, is about 10% [34].

4.2 Tight selection

Two additional requirements define the tight event selection used for the signal search. The first is the presence of small missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$). In PF reconstruction, $E_{\mathrm{T}}^{\mathrm{miss}}$ is defined as the modulus of the vector sum of the transverse momenta of all reconstructed particles (charged and neutral) in the event. The jet energy scale corrections are also used to correct the $E_{\mathrm{T}}^{\mathrm{miss}}$ value [35]. In order to pass the tight selection, events are required to have $E_{\mathrm{T}}^{\mathrm{miss}} < 20\,\mathrm{GeV}$. The validity of the simulation for low-$E_{\mathrm{T}}^{\mathrm{miss}}$ events is verified using a data sample enriched in Z+4 jets $\rightarrow \mu^+\mu^-$+4 jets events. Events in this sample are required to have at least four jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}/c$ and $|\eta| < 2.4$ in addition to two muons with $p_{\mathrm{T}} > 20\,\mathrm{GeV}/c$, $|\eta| < 2.1$, $I_{\mathrm{rel}}^{\ell} < 0.1$, and invariant mass in the range 76–104 GeV/c^2. The $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions obtained in data and simulation for this event sample are shown in Fig. 1. The simulated distribution is normalized to that observed in data and the two agree within statistical uncertainties. The disagreement in overall yield before normalization is at the level of 7%, which is covered by statistical and theoretical [36] uncertainties.

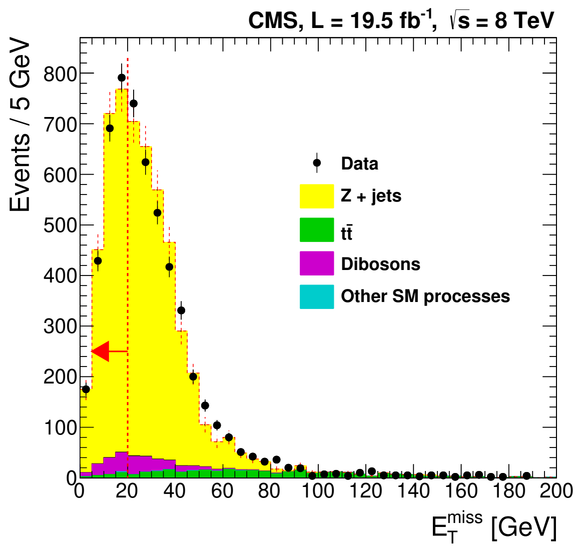

Figure 1: Distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$ in both data and simulation for a sample of events enriched in $\mathrm{Z} + 4\,\mathrm{jets} \rightarrow \mu^+\mu^- + 4\,\mathrm{jets}$ events. The simulated distribution is normalized to that observed in data. For both data and simulation the error bars indicate the statistical uncertainty. The vertical dashed line and the arrow indicate the $E_{\mathrm{T}}^{\mathrm{miss}}$ signal region used in this analysis. The total contribution from other SM processes, such as single-top-quark, W+jets, $\mathrm{t\bar{t}}$ W, and $\mathrm{t\bar{t}}$ Z productions is very small and is hardly visible in the plot.

The second requirement for an event to pass the tight selection is the compatibility of its kinematic properties with the final state produced by $\mathrm{t\bar{t}}$ events where one top quark has a fully hadronic SM decay and the other the BNV decay. This compatibility is tested using the following variable:

$$\chi^2 = \sum_i \frac{(x_i - \bar{x}_i)^2}{\sigma_i^2}, \tag{2}$$

where the x_i are the reconstructed invariant mass of the W boson from the hadronically decaying top quark, the reconstructed invariant mass of the hadronically decaying top quark, and the reconstructed invariant mass of the top quark with the BNV decay. The values of $\bar{x}_i$ and σ_i are the expectation values and standard deviations of Gaussian fits to the x_i distributions obtained from simulated $t\bar{t}$ events with the two top quarks undergoing the BNV and the fully hadronic SM decay, respectively. Simulation information is used to obtain the correct jet-to-parton association. The number of jet combinations is reduced by not associating jets tagged by the CSV algorithm with the W decay. All other combinations in the event are considered and the one with the smallest χ^2 is retained. For signal events, the correct jet combination is expected to be chosen in about 60% of the cases. In the tight selection, the smallest χ^2 is required to be less than 20.

The values of the thresholds on the lepton p_{T}, $E_{\mathrm{T}}^{\mathrm{miss}}$, χ^2, as well as the configuration of the b-tagging algorithm were chosen by minimizing the expected upper limit on $\mathcal{B}$ at 95% confidence level (CL). This procedure also retains high sensitivity for an observation of a BNV decay.

5 Signal search strategy

The search proceeds in the following way: for each assumed value of $\mathcal{B}$, the expected contributions from $t\bar{t}$ ($N_{t\bar{t}}^{\mathrm{B}}$) and tW ($N_{\mathrm{tW}}^{\mathrm{B}}$) production to the yield in the basic selection are scaled such that the total expected yield is normalized to the observed number of events ($N_{\mathrm{obs}}^{\mathrm{B}}$). The sum of the $t\bar{t}$ and tW yields in the tight selection ($N_{\mathrm{top}}^{\mathrm{T}}$) is then extracted using the efficiencies, $\epsilon_{t\bar{t}}^{(\mathrm{T}|\mathrm{B})}$ and $\epsilon_{\mathrm{tW}}^{(\mathrm{T}|\mathrm{B})}$, to pass the tight selection for $t\bar{t}$ and tW events that satisfy the basic selection criteria. Finally, the comparison between the total expected and observed numbers of events in the tight selection, which is significantly more efficient for the signal than for the background, is used to infer the presence of a signal or set an upper limit on $\mathcal{B}$. The impact of a number of systematic uncertainties is significantly reduced as a result of the normalization of simulation to data in the basic selection. Indeed, using this approach, the expected upper limit at 95% CL on $\mathcal{B}$ is found to improve by a factor of 2.5, while the expected significance of a signal-like deviation from SM expectations increases from about 1.2 standard deviations to 3.6 for a signal with $\mathcal{B} = 0.005$. In this procedure we thus neglect the contributions to a possible BNV signal from events with single-top-quark production via *s*- and *t*-channels, $t\bar{t}$ W, and $t\bar{t}$ Z, which are treated as non-top background. These contributions are expected to be negligible, as can be inferred from the yields of these processes given in Tables 1 and 2, as estimated from simulation.

Following the approach outlined above, the expression for the expected total yield in the tight selection ($N_{\mathrm{exp}}^{\mathrm{T}}$) is:

$$N_{\mathrm{exp}}^{\mathrm{T}} = N_{\mathrm{top}}^{\mathrm{T}} + N_{\mathrm{bck}}^{\mathrm{T}} = \left(N_{\mathrm{obs}}^{\mathrm{B}} - N_{\mathrm{bck}}^{\mathrm{B}}\right) \left[\frac{N_{t\bar{t}}^{\mathrm{B}}}{N_{t\bar{t}}^{\mathrm{B}} + N_{\mathrm{tW}}^{\mathrm{B}}} \cdot \epsilon_{t\bar{t}}^{(\mathrm{T}|\mathrm{B})} + \frac{N_{\mathrm{tW}}^{\mathrm{B}}}{N_{t\bar{t}}^{\mathrm{B}} + N_{\mathrm{tW}}^{\mathrm{B}}} \cdot \epsilon_{\mathrm{tW}}^{(\mathrm{T}|\mathrm{B})}\right] + N_{\mathrm{bck}}^{\mathrm{T}}, \tag{3}$$

where $N_{\mathrm{bck}}^{\mathrm{B}}$ ($N_{\mathrm{bck}}^{\mathrm{T}}$) is the yield of the non-top background (including *s*- and *t*-channel single-top-quark, $t\bar{t}$ W, and $t\bar{t}$ Z production events, as discussed above) in the basic (tight) selection.

All the quantities in the square brackets of Eq. (3) are functions of $\mathcal{B}$ and can be expressed in terms of the $t\bar{t}$ and tW cross sections ($\sigma_{t\bar{t}}$ and σ_{tW}, respectively), integrated luminosity, and efficiencies for passing the basic and tight selections. In terms of these variables, Eq. (3) becomes:

$$N_{\mathrm{exp}}^{\mathrm{T}} = \left(N_{\mathrm{obs}}^{\mathrm{B}} - N_{\mathrm{bck}}^{\mathrm{B}}\right) \left[\frac{1}{1 + \frac{\sigma_{\mathrm{tW}}\epsilon_{\mathrm{tW}}^{\mathrm{B}}(\mathcal{B})}{\sigma_{t\bar{t}}\epsilon_{t\bar{t}}^{\mathrm{B}}(\mathcal{B})}} \cdot \frac{\epsilon_{t\bar{t}}^{\mathrm{T}}(\mathcal{B})}{\epsilon_{t\bar{t}}^{\mathrm{B}}(\mathcal{B})} + \frac{1}{1 + \frac{\sigma_{t\bar{t}}\epsilon_{t\bar{t}}^{\mathrm{B}}(\mathcal{B})}{\sigma_{\mathrm{tW}}\epsilon_{\mathrm{tW}}^{\mathrm{B}}(\mathcal{B})}} \cdot \frac{\epsilon_{\mathrm{tW}}^{\mathrm{T}}(\mathcal{B})}{\epsilon_{\mathrm{tW}}^{\mathrm{B}}(\mathcal{B})}\right] + N_{\mathrm{bck}}^{\mathrm{T}}. \tag{4}$$

In Eq. (4), $\epsilon_{t\bar{t}}^{\mathrm{B}}$ ($\epsilon_{t\bar{t}}^{\mathrm{T}}$) indicates the efficiency of the basic (tight) selection for $t\bar{t}$ events. Similarly, $\epsilon_{\mathrm{tW}}^{\mathrm{B}}$ ($\epsilon_{\mathrm{tW}}^{\mathrm{T}}$) indicates the efficiency of the basic (tight) selection for tW events. Each of these four efficiency values is a function of $\mathcal{B}$ and of three (for $\mathrm{t\bar{t}}$ events) or two (for tW events) efficiency values, which correspond to the different decay modes:

$$\epsilon^{\mathrm{X}}_{\mathrm{t\bar{t}}}(\mathcal{B}) = 2\mathcal{B}(1-\mathcal{B})\epsilon^{\mathrm{X}}_{\mathrm{BNV,SM}} + (1-\mathcal{B})^2\epsilon^{\mathrm{X}}_{\mathrm{SM,SM}} + \mathcal{B}^2\epsilon^{\mathrm{X}}_{\mathrm{BNV,BNV}}, \tag{5}$$

$$\epsilon^{\mathrm{X}}_{\mathrm{tW}}(\mathcal{B}) = (1-\mathcal{B})\epsilon^{\mathrm{X}}_{\mathrm{SM}} + \mathcal{B}\epsilon^{\mathrm{X}}_{\mathrm{BNV}}, \tag{6}$$

where X = B, T with B and T denoting the basic and tight selection, respectively, and SM (BNV) indicating the SM (BNV) decay mode of the top quark. With the adopted approach, the search is mostly sensitive to uncertainties in the ratio of $\epsilon^{\mathrm{T}}_{\mathrm{SM,SM}}$ to $\epsilon^{\mathrm{B}}_{\mathrm{SM,SM}}$, $N^{\mathrm{B}}_{\mathrm{bck}}$ and $N^{\mathrm{T}}_{\mathrm{bck}}$.

6 Background evaluation

In order to evaluate the expected yield in the tight selection (Eq. (4)), a number of backgrounds need to be estimated.

6.1 Top-quark and electroweak backgrounds

The main background in this analysis is from $\mathrm{t\bar{t}}$ events where one of the two top quarks decays to a lepton, a neutrino, and a b jet while the other one decays to three jets. As described in Section 5, the estimates of the $\mathrm{t\bar{t}}$ and tW yields require knowledge of the efficiencies for $\mathrm{t\bar{t}}$ and tW events, which satisfy the basic selection criteria, to also pass the tight selection. These efficiencies are obtained from simulation. The required $\mathrm{t\bar{t}}$ and tW cross sections are obtained from the MCFM [37] next-to-leading order (NLO) predictions.

The second-largest background is represented by W and Z production in association with jets. The theoretical predictions for the $\mathrm{W} + \text{jets} \rightarrow l\nu + \text{jets}$ and $\mathrm{Z}/\gamma^* + \text{jets} \rightarrow \ell\ell + \text{jets}$ processes, where ℓ indicates a lepton, are computed by FEWZ [38, 39] at next-to-next-to-leading order (NNLO). The efficiencies for events produced by these processes to pass the basic and tight selections are evaluated from simulation and, using the measured value of the integrated luminosity [40], the yields in the basic and tight selections are obtained.

The contributions to the yield in the basic and tight selections from single-top-quark production via *s*- and *t*-channel processes, and from WW, WZ, ZZ, $\mathrm{t\bar{t}W}$, and $\mathrm{t\bar{t}Z}$ production, are also evaluated from simulation. The cross section value for single-top-quark production via *s*-channel is computed using next-to-next-to-leading-logarithm resummation of soft and collinear gluon corrections [41]. The cross section values for $\mathrm{t\bar{t}W}$ and $\mathrm{t\bar{t}Z}$ are computed at leading-order (LO) as provided by MADGRAPH, including the contributions at LO from processes yielding one extra jet. In all other cases the NLO theoretical predictions, as obtained from MCFM, are used. The sum of yields predicted by the simulation for all these processes is less than 1% of the total expected yield in both the basic and tight selections.

All cross section values used in the analysis are listed in the second column of Tables 1 and 2. The yields reported in these tables are discussed in Section 8.

6.2 QCD multijet background

The QCD multijet background yields are evaluated with two methods, depending on the event selection.

In the first method the isolation thresholds for the leptons are inverted (becoming $0.12 < I^{\ell}_{\mathrm{rel}} < 0.2$ for muons and $0.1 < I^{\ell}_{\mathrm{rel}} < 0.2$ for electrons) in order to enhance the presence of QCD multijet events. These selections are denoted as anti-isolated basic and anti-isolated tight in

Table 1: Muon channel: assumed cross section values, expected (as discussed in Section 6) and observed yields in the basic and tight selections for an assumed $\mathcal{B}$ value of zero. The "Basic" and "Corrected basic" columns report the yields in the basic selection before and after the normalization procedure described in Section 5. The uncertainties include both statistical and systematic contributions.

Process	Cross section (pb)	Basic	Corrected basic	Tight
$t\bar{t}$	234	36900 ± 8900	38600 ± 3600	2200 ± 220
W+jets	37500	6300 ± 3200		230 ± 120
Z+jets	3500	380 ± 190		32 ± 18
tW	22.2	1160 ± 180	1210 ± 280	51 ± 12
t-channel	87.1	250 ± 130		5.7 ± 3.0
s-channel	5.55	31 ± 16		0.84 ± 0.52
WW	54.8	86 ± 43		3.1 ± 1.7
WZ	33.2	41 ± 21		1.43 ± 0.78
ZZ	17.7	5.5 ± 2.8		0.49 ± 0.28
$t\bar{t}$W	0.23	128 ± 64		5.9 ± 3.0
$t\bar{t}$Z	0.17	79 ± 40		4.1 ± 2.1
QCD	—	790 ± 550		119 ± 59
Total exp.	—	46000 ± 9700	47951 ± 220	2660 ± 130
Data	—	47951		2614

Table 2: Electron channel: assumed cross section values, expected (as discussed in Section 6) and observed yields in the basic and tight selections for an assumed $\mathcal{B}$ value of zero. The "Basic" and "Corrected basic" columns report the yields in the basic selection before and after the normalization procedure described in Section 5. The uncertainties include both statistical and systematic contributions.

Process	Cross section (pb)	Basic	Corrected basic	Tight
$t\bar{t}$	234	36400 ± 8600	38200 ± 3600	2030 ± 210
W+jets	37500	6500 ± 3300		240 ± 120
Z+jets	3500	760 ± 380		85 ± 45
tW	22.2	1110 ± 170	1170 ± 270	37.2 ± 7.5
t-channel	87.1	230 ± 120		6.6 ± 3.6
s-channel	5.55	27 ± 14		0.70 ± 0.50
WW	54.8	78 ± 39		3.7 ± 2.0
WZ	33.2	45 ± 23		2.1 ± 1.1
ZZ	17.7	11.0 ± 5.6		1.40 ± 0.70
$t\bar{t}$W	0.23	132 ± 66		6.2 ± 3.1
$t\bar{t}$Z	0.17	86 ± 43		4.4 ± 2.2
QCD	—	2900 ± 1500		330 ± 170
Total exp.	—	48300 ± 10400	50108 ± 220	2740 ± 160
Data	—	50108		2703

Table 3: Muon and electron channels: numbers relevant for the estimate of the QCD multijet yield based on the misidentification rate measurement (Eq. (7)). Only the average value of f is reported, while values computed in bins of p_{T} are used in the analysis.

Muon channel

Selection	$N_{\mathrm{data}}^{\mathrm{antiiso}}$	$N_{\mathrm{nonQCD}}^{\mathrm{antiiso}}$	f	N_{QCD}
Tight	412	257 ± 61	0.44 ± 0.09	119 ± 60

Electron channel

Selection	$N_{\mathrm{data}}^{\mathrm{antiiso}}$	$N_{\mathrm{nonQCD}}^{\mathrm{antiiso}}$	f	N_{QCD}
Basic	7162	4400 ± 950	0.51 ± 0.10	2900 ± 1400
Tight	542	222 ± 53	0.51 ± 0.10	330 ± 160

the following, as opposed to the (isolated) basic and tight selections used in the analysis. The yield of the QCD multijet background in either the tight or basic selection (N_{QCD}) can thus be inferred using the following equation:

$$N_{\mathrm{QCD}} = R \cdot (N_{\mathrm{data}}^{\mathrm{antiiso}} - N_{\mathrm{nonQCD}}^{\mathrm{antiiso}}), \tag{7}$$

where R is the ratio of the numbers of QCD multijet events in the isolated and anti-isolated selections, $N_{\mathrm{data}}^{\mathrm{antiiso}}$ is the yield observed in data in the anti-isolated selection, and $N_{\mathrm{nonQCD}}^{\mathrm{antiiso}}$ is the contribution in the anti-isolated selection from other SM processes. The value of $N_{\mathrm{nonQCD}}^{\mathrm{antiiso}}$ is estimated from the simulation using the cross section values discussed in Section 6.1. The value of R is estimated from data using the approximation $R = f/(1-f)$, where f is the so-called "misidentification rate". The misidentification rate is defined as the probability that a genuine jet that has passed all lepton-identification criteria and a looser isolation threshold ($I_{\mathrm{Rel}}^{\ell} < 0.2$) also passes the final analysis isolation threshold. The value of f is obtained from data as a function of the lepton p_{T} using a sample of events enriched in $\mathrm{Z} + \mathrm{jets} \to \mu^{+}\mu^{-} +$ jets events. The estimate of the QCD multijet yield is then determined using Eq. (7) in each muon p_{T} bin. The misidentification rate is measured with events whose topology is different from that of events in the final selection. This method gives rise to the dominant uncertainty in the estimation of the misidentification rate, which is assumed to be 20%. The systematic uncertainty in $N_{\mathrm{nonQCD}}^{\mathrm{antiiso}}$ is in the range 20–25% depending on the selection. After taking into account also the statistical uncertainties, an overall uncertainty of 50% is assigned to the QCD multijet yield in the electron selections and in the muon tight selection. In the case of the muon basic selection the systematic uncertainty in $N_{\mathrm{nonQCD}}^{\mathrm{antiiso}}$ is larger than the difference $N_{\mathrm{data}}^{\mathrm{antiiso}} - N_{\mathrm{nonQCD}}^{\mathrm{antiiso}}$ and therefore prevents a sufficiently accurate estimate of the QCD multijet yield. For this reason, a second method, which is described below, is used for this specific selection. In the electron analysis the uncertainties in the QCD multijet background estimates in the basic and tight selections are treated as fully and positively correlated. The numbers relevant for the QCD multijet yield estimation with this first method are given in Table 3.

In the second method the assumption is made that $E_{\mathrm{T}}^{\mathrm{miss}}$ and χ^2 are not correlated for QCD multijet events, and the estimated QCD multijet yield in the basic selection ($N_{\mathrm{QCD}}^{\mathrm{B}}$) is obtained from the following equation:

$$N_{\mathrm{QCD}}^{\mathrm{B}} = \frac{N_{\mathrm{QCD}}^{\mathrm{T}}}{\epsilon_{E_{\mathrm{T}}^{\mathrm{miss}}} \epsilon_{\chi^2}}, \tag{8}$$

where $N_{\mathrm{QCD}}^{\mathrm{T}}$ is the QCD multijet yield in the tight selection, as obtained with the first method, and $\epsilon_{E_{\mathrm{T}}^{\mathrm{miss}}}$ (ϵ_{χ^2}) is the probability that a QCD event that passes the basic selection has $E_{\mathrm{T}}^{\mathrm{miss}} <$

Table 4: Muon channel: numbers relevant for the estimate of the QCD multijet yield based on Eq. (8). As stated in the text, this method is only used for the muon basic selection.

Muon channel			
Selection	$\epsilon_{E_{\mathrm{T}}^{\mathrm{miss}}}$	ϵ_{χ^2}	$N_{\mathrm{QCD}}^{\mathrm{B}}$
Basic	0.33 ± 0.12	0.45 ± 0.16	790 ± 550

20 GeV ($\chi^2 < 20$). The values of $\epsilon_{E_{\mathrm{T}}^{\mathrm{miss}}}$ and ϵ_{χ^2} are taken from simulation. A total uncertainty of 50% in the product of $\epsilon_{E_{\mathrm{T}}^{\mathrm{miss}}}$ and ϵ_{χ^2} is assumed, which yields, together with the 50% uncertainty in $N_{\mathrm{QCD}}^{\mathrm{T}}$, an overall 70% uncertainty in the estimate of the QCD multijet background in the muon basic selection. The partial correlation with the uncertainty in the QCD multijet background estimate in the muon tight selection is taken into account when determining the final results of the analysis. The numbers relevant for the QCD multijet yield estimation in the muon basic selection with this second method are given in Table 4.

In the electron analysis the contribution of γ+jets processes can potentially give rise to events that pass the basic and the tight selections. The isolated photon in the event can convert before reaching the calorimeters and be identified as a single isolated electron. From simulation studies it turns out that the central values of the QCD yields estimated with the first method in both the basic and tight selections need to be increased by 2% to account for this contribution.

7 Systematic uncertainties

The observable of the likelihood function used in the analysis is the yield in data for the tight selection ($N_{\mathrm{obs}}^{\mathrm{T}}$), while the parameter of interest is $\mathcal{B}$. A number of other quantities appear in the likelihood function and affect the estimate of $N_{\mathrm{exp}}^{\mathrm{T}}$. They are $N_{\mathrm{bck}}^{\mathrm{B}}$, $N_{\mathrm{bck}}^{\mathrm{T}}$, the ratio $\sigma_{\mathrm{tW}}/\sigma_{\mathrm{t\bar{t}}}$, and the ten efficiencies in Eq. (4). They are estimated as described in Section 6. Many of these quantities are correlated because of common sources of systematic uncertainties. These correlations are handled using the method presented in Ref. [42], where the jth source of systematic uncertainty is associated with a nuisance parameter of true value u_j constrained by a normal probability density function (PDF) $\mathcal{G}(u_j)$. The method results in the parameterization, $\theta_i(u_j)$, of the i-th likelihood quantity θ_i in terms of all the u_j nuisance parameters. Other quantities in the likelihood function are instead either assumed to be independent of any other (σ_{tW}, $\sigma_{\mathrm{t\bar{t}}}$, and $N_{\mathrm{obs}}^{\mathrm{B}}$) or correlated with a single other quantity (the QCD multijet contributions to $N_{\mathrm{bck}}^{\mathrm{B}}$ and $N_{\mathrm{bck}}^{\mathrm{T}}$). In these cases the quantities are simply constrained in the likelihood function by a lognormal PDF $\rho_k(\tilde{\theta}_k|\theta_k)$, which describes the probability of measuring a value $\tilde{\theta}_k$ for the kth likelihood quantity should its true value be θ_k, and which takes into account possible correlations. With this approach, the likelihood function $\mathcal{L}$ reads:

$$\mathcal{L}(N_{\mathrm{obs}}^{\mathrm{T}} \,|\, \mathcal{B}, \theta_i(u_j), \theta_k) = \mathcal{P}\left(N_{\mathrm{obs}}^{\mathrm{T}} \,|\, N_{\mathrm{exp}}^{\mathrm{T}}(\mathcal{B}, \theta_i(u_j), \theta_k)\right) \cdot \prod_j \mathcal{G}(u_j) \cdot \prod_k \rho(\tilde{\theta}_k \,|\, \theta_k), \tag{9}$$

where $\mathcal{P}\left(N_{obs}^{\mathrm{T}} \,|\, N_{\mathrm{exp}}^{\mathrm{T}}(\mathcal{B}, \theta_i(u_j), \theta_k)\right)$ indicates the Poisson PDF evaluated at $N_{\mathrm{obs}}^{\mathrm{T}}$ and with expectation value $N_{\mathrm{exp}}^{\mathrm{T}}(\mathcal{B}, \theta_i(u_j), \theta_k)$ given by Eq. (4).

The sources of systematic uncertainty are discussed below. Unless specified otherwise, each source of systematic uncertainty is varied by ± 1 standard deviation to infer the relative variation in each of the quantities appearing in the likelihood function.

The uncertainty in the simulated jet energy scale depends on the jet p_{T} and η, and is smaller than 3% [33]. This uncertainty is also propagated to the simulated $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation. It induces uncertainties of the order of 10% in the efficiency values and in the W/Z+jets contributions to $N_{\mathrm{bck}}^{\mathrm{B}}$ and $N_{\mathrm{bck}}^{\mathrm{T}}$, but its impact on the final limits remains very limited because of the highly correlated effects on these quantities.

The jet energy resolution is varied in the simulation within its uncertainty, which is of the order of 10% [33]. This uncertainty is also propagated into the simulated $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation. Although it induces a relative change in the efficiency values and in the W/Z+jets yield of less than 5%, it is one of the sources of uncertainty with the largest impact on the final limits.

The uncertainty in the yield of the QCD multijet background is discussed in Section 6.2. This uncertainty has a significant impact only in the electron analysis, where its effect is comparable to that of the jet energy resolution uncertainty.

The uncertainties in the cross section values of the W+jets and Z+jets backgrounds largely dominate the uncertainty in the values of $N_{\mathrm{bck}}^{\mathrm{B}}$ and $N_{\mathrm{bck}}^{\mathrm{T}}$ for the muon analysis, whereas in the electron analysis they are comparable to the uncertainty in the QCD contribution. As described in Section 6, the W+jets and Z+jets cross section values used in this analysis are the theoretical inclusive predictions, which have an uncertainty of about 5% [43]. The CMS measurement [44] of the ratio of the W+4 jets to the inclusive W cross section (the result for W+5 jets is not available) is in agreement with the MADGRAPH predictions within the measurement uncertainty, which is at the level of 30%. In addition, the limited number of events in the simulated W+jets and Z+jets samples introduces a statistical uncertainty of about 10% in the yield of these processes in the tight selection. Taking these contributions into account, a conservative uncertainty of 50% in the W+jets and Z+jets cross sections is assumed. This uncertainty is found to have an impact comparable to that of the jet energy resolution on the final limits.

Other theoretical uncertainties, such as those in the parton distribution functions, the modeling of initial- and final-state radiation, and the factorization and renormalization scales are also evaluated and are all found to have an impact on the final limits comparable to that of the jet energy resolution uncertainty. In the case of the parton distribution functions, the simulated samples are generated using the CTEQ 6.6 library [45] and the impact of their uncertainty is obtained by varying 22 independent parameters within their uncertainties.

A number of other sources of systematic uncertainties are found to have a negligible impact on the final results. They are summarized in the following. The uncertainty in the efficiency of the lepton trigger, identification, and isolation is assessed to be 5% [30, 31] for both muons and electrons. Unclustered reconstructed particles are also used to compute $E_{\mathrm{T}}^{\mathrm{miss}}$ [35], and thus an uncertainty in the model provided by simulation of these particles is reflected in an uncertainty in the final $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation. The associated systematic uncertainty is estimated by varying the contribution of unclustered particles to $E_{\mathrm{T}}^{\mathrm{miss}}$ by $\pm 10\%$. An uncertainty of 5% in the estimated mean number of pileup collisions is assumed. An uncertainty of 2.6% is assigned to the integrated luminosity [40]. This uncertainty affects only $N_{\mathrm{bck}}^{\mathrm{B}}$ and $N_{\mathrm{bck}}^{\mathrm{T}}$, but is negligible compared with other sources of uncertainty. The uncertainty in the b-tagging efficiency results in an uncertainty in the event selection efficiency in the range 1% to 5% depending on the number, energy, η, and type of the jets in the event [34]. The consequent uncertainty induced in $N_{\mathrm{exp}}^{\mathrm{T}}$ is about 3% for both the muon and electron channels. The uncertainties in the $\mathrm{t\bar{t}}$ and tW production cross section values are 15% and 8%, respectively. These two uncertainties affect the ratio $\sigma_{\mathrm{tW}}/\sigma_{\mathrm{t\bar{t}}}$ in Eq. (4) and are conservatively assumed to be uncorrelated. The uncertainties in the yields from the WW, WZ, and ZZ processes, as well as from s- and t-channel single-top-quark production are neglected since these processes make only small contributions to $N_{\mathrm{bck}}^{\mathrm{B}}$ and $N_{\mathrm{bck}}^{\mathrm{T}}$.

The central values and the overall uncertainties in the quantities used for the calculation of the likelihood function are reported in Table 5 for both the muon and electron analyses.

Table 5: Central values and associated overall uncertainties for the quantities appearing in the likelihood function.

Quantity	Muon channel	Electron channel
$\epsilon^{\mathrm{B}}_{\mathrm{SM,SM}}$	$(8.1 \pm 1.5) \times 10^{-3}$	$(8.0 \pm 1.5) \times 10^{-3}$
$\epsilon^{\mathrm{T}}_{\mathrm{SM,SM}}$	$(4.62 \pm 0.93) \times 10^{-4}$	$(4.24 \pm 0.85) \times 10^{-4}$
$\epsilon^{\mathrm{B}}_{\mathrm{BNV,SM}}$	$(7.37 \pm 0.89) \times 10^{-2}$	$(7.33 \pm 0.88) \times 10^{-2}$
$\epsilon^{\mathrm{T}}_{\mathrm{BNV,SM}}$	$(1.86 \pm 0.32) \times 10^{-2}$	$(1.62 \pm 0.27) \times 10^{-2}$
$\epsilon^{\mathrm{B}}_{\mathrm{BNV,BNV}}$	$(1.00 \pm 0.16) \times 10^{-2}$	$(1.55 \pm 0.25) \times 10^{-2}$
$\epsilon^{\mathrm{T}}_{\mathrm{BNV,BNV}}$	$(1.74 \pm 0.32) \times 10^{-3}$	$(2.64 \pm 0.55) \times 10^{-3}$
$\epsilon^{\mathrm{B}}_{\mathrm{SM}}$	$(2.68 \pm 0.32) \times 10^{-3}$	$(2.57 \pm 0.31) \times 10^{-3}$
$\epsilon^{\mathrm{T}}_{\mathrm{SM}}$	$(1.13 \pm 0.14) \times 10^{-4}$	$(8.21 \pm 0.99) \times 10^{-5}$
$\epsilon^{\mathrm{B}}_{\mathrm{BNV}}$	$(2.72 \pm 0.42) \times 10^{-2}$	$(2.80 \pm 0.42) \times 10^{-2}$
$\epsilon^{\mathrm{T}}_{\mathrm{BNV}}$	$(5.38 \pm 0.84) \times 10^{-3}$	$(5.84 \pm 0.82) \times 10^{-3}$
$N^{\mathrm{B}}_{\mathrm{bck}}$	8100 ± 3400	10800 ± 3800
$N^{\mathrm{T}}_{\mathrm{bck}}$	400 ± 140	680 ± 230
$N^{\mathrm{B}}_{\mathrm{obs}}$	47951 ± 220	50108 ± 220
σ_{tW}	22.2 ± 1.8 pb	
$\sigma_{\mathrm{t\bar{t}}}$	234 ± 35 pb	

8 Results

Tables 1 and 2 report the yields expected from the different SM processes considered, and the yields observed in data for the muon and electron channels, respectively. In these tables $\mathcal{B}$ is assumed to be zero. The yields of the $\mathrm{t\bar{t}}$ and tW processes in the basic selection before and after the normalization procedure described in Section 5 are both reported, the yields before normalization being simply calculated as the products of the theoretical cross sections, the measured values of the integrated luminosity, and the event selection efficiencies obtained from simulation. In both the muon and electron channels the observed total yield in the tight selection agrees with the SM expectations.

Figure 2 (3) shows, for the muon (electron) channel, the observed and expected distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$ and χ^2 for the basic and tight selections assuming no BNV top-quark decays. The signal distribution expected for $\mathcal{B} = 0.005$ is also shown. The methods adopted for the QCD multijet background estimates provide no detailed shape information for this contribution. Thus, for the sake of illustration in the plots, the shape of the QCD multijet background contribution in the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution is obtained from simulation using events with at least three jets, instead of five, in order to reduce large statistical fluctuations. In the case of the χ^2 variable, whose calculation requires events with at least five jets, the shape of the QCD multijet background contribution is obtained from data in the anti-isolated regions defined in Section 6.2 after subtraction of the top-quark and electro-weak components estimated from simulation. The discrepancy visible between the observed and expected $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions in the electron channel basic selection can be accommodated with the 50% uncertainty assumed in the QCD total yield. These distributions are presented for purposes of illustration and are not used in the analysis.

The observed data samples are then used to calculate upper limits on the value of $\mathcal{B}$. The upper limit on $\mathcal{B}$ at 95% CL is obtained with the Feldman–Cousins approach [46]. Pseudoexperiments are generated using the frequentist prescription described in Ref. [47]. The results are summarized in Table 6 for the muon and electron channels, and for their combination. The combined results are obtained by maximizing the product of the two likelihood functions, assuming a common value of $\mathcal{B}$ for the two channels. Full correlation is assumed for each pair of corresponding nuisance parameters in the two analyses, except for those related to the lepton trigger, identification, and isolation, which are assumed to be independent. The combination of the muon and electron datasets does not significantly improve the upper limit because of the dominant systematic uncertainties related to the modeling of jets, $E_{\mathrm{T}}^{\mathrm{miss}}$, and event kinematic properties, which are fully correlated across the two channels.

Table 6: Observed 95% CL upper limit on $\mathcal{B}$, expected median 95% CL limit for the $\mathcal{B} = 0$ hypothesis and ranges that are expected to contain 68% of all observed deviations from the expected median for the muon and electron channels and for their combination.

Channel	95% CL	Expected	68% CL exp. range
Muon	0.0016	0.0029	[0.0017, 0.0042]
Electron	0.0017	0.0029	[0.0017, 0.0044]
Combined	0.0015	0.0029	[0.0016, 0.0044]

9 Summary

Data recorded by the CMS detector have been used to search for baryon number violation in top-quark decays. The data correspond to an integrated luminosity of $19.52 \pm 0.49\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$. No significant excess is observed over the SM expectation for events with one isolated lepton (either a muon or an electron), at least five jets of which at least one is b tagged, and low missing transverse energy. These results are used to set an upper limit of 0.0016 (0.0017) at 95% confidence level on the branching fraction of a hypothetical baryon number violating top-quark decay into a muon (electron) and 2 jets. These limits on baryon number violation are the first that have been obtained for a process involving the top quark.

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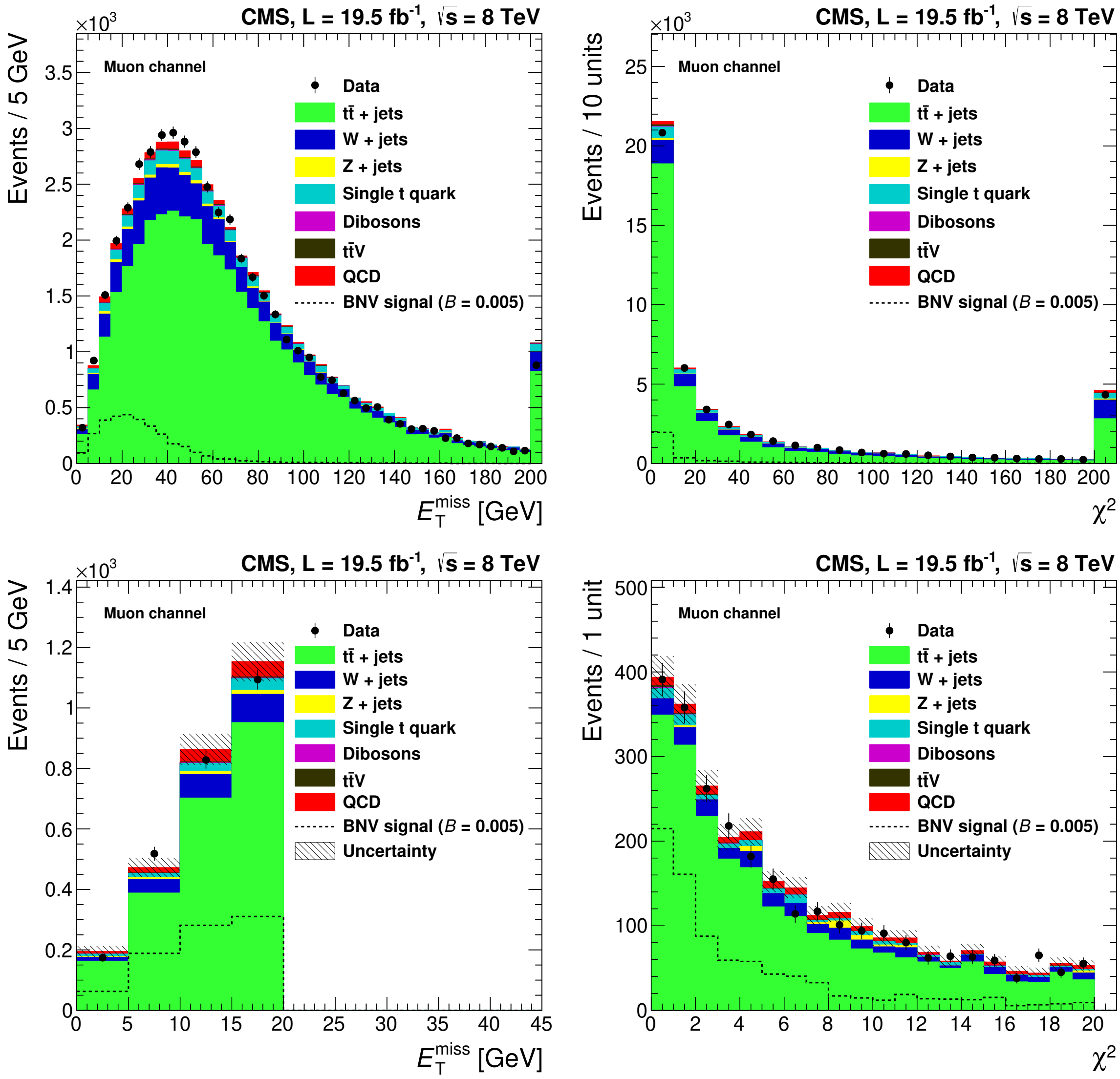

Figure 2: Muon channel: observed and SM expected distributions of E_T^{miss} (left) and χ^2 (right). The signal contribution expected for a branching fraction $\mathcal{B} = 0.005$ for the baryon number violating top-quark decay is also shown. Top: distributions for the basic selection; because of the normalization to data, the integrals of the two distributions are equal; overflowing entries are included in the last bins of the distributions. Bottom: distributions for the tight selection; the shaded band indicating the total uncertainty in the expected yield is estimated assuming that the systematic relative uncertainty has no dependence on E_T^{miss} or χ^2.

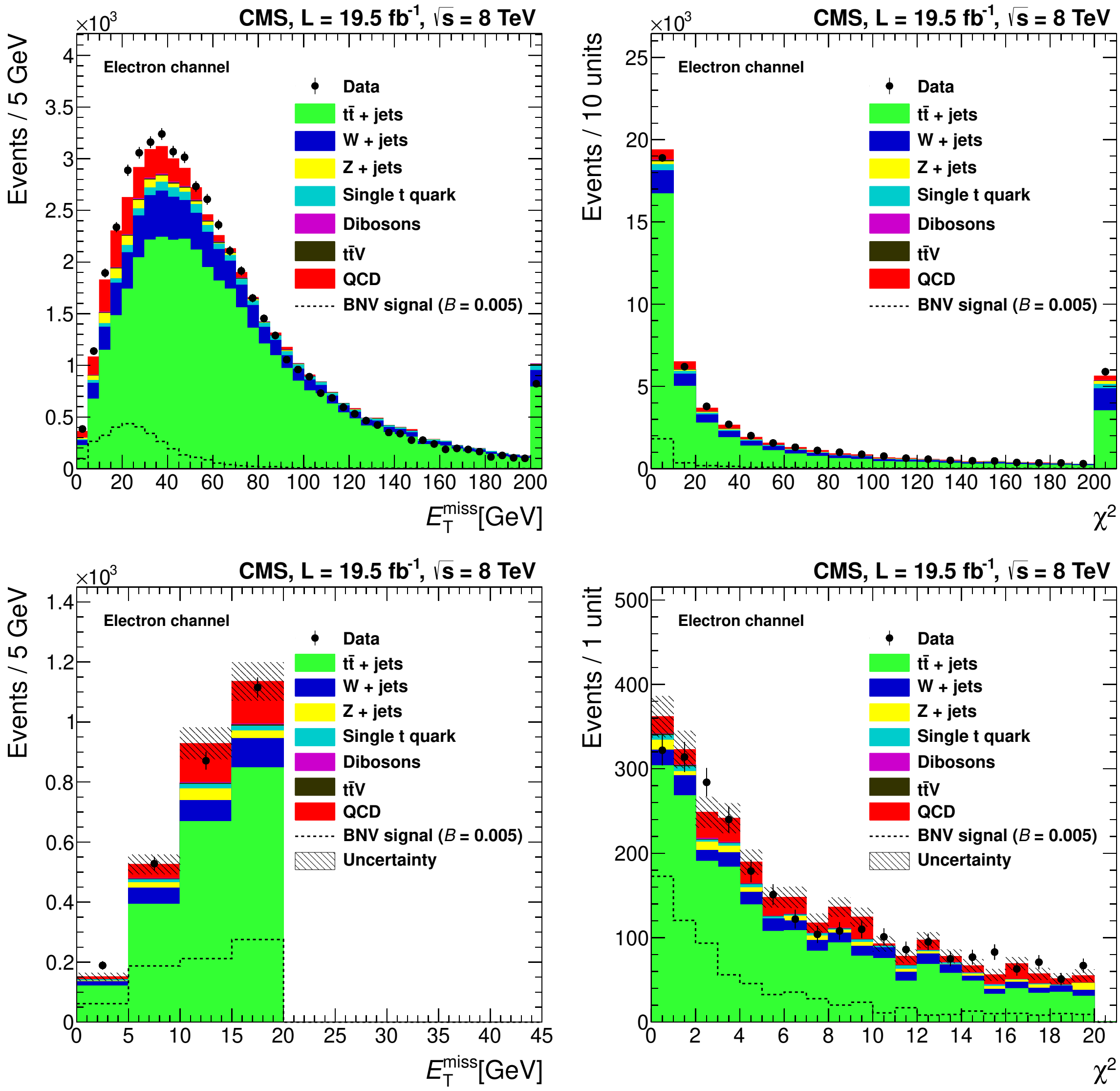

Figure 3: Electron channel: observed and SM expected distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$ (left) and χ^2 (right). The signal contribution expected for a branching fraction $\mathcal{B} = 0.005$ for the baryon number violating top-quark decay is also shown. Top: distributions for the basic selection; because of the normalization to data, the integrals of the two distributions are equal; overflowing entries are included in the last bins of the distributions. Bottom: distributions for the tight selection; the shaded band indicating the total uncertainty in the expected yield is estimated assuming that the systematic relative uncertainty has no dependence on $E_{\mathrm{T}}^{\mathrm{miss}}$ or χ^2.

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